Two aspects of decadal ENSO variability modulating the long-term global carbon cycle

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Key Points:
- About 36% of decadal variations in global NBP can be explained by two aspects of decadal ENSO variability
- First, decadal ENSO-like variability induces interdecadal changes in terrestrial carbon fluxes via atmospheric teleconnections
- Second, decadal ENSO modulations in amplitude and asymmetry lead to decadal NBP variability by changing ENSO-induced residual NBP

Supporting Information:
- Supporting Information S1

Correspondence to:
J.-S. Kim and J.-S. Kug,
jinsoo.kim@uzh.ch;
jskug@postech.ac.kr

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Two Aspects of Decadal ENSO Variability Modulating the Long-Term Global Carbon Cycle

So-Won Park[1], Jin-Soo Kim[2,3,4], Jong-Seong Kug[1], Malte F. Stuecker[5,6,7], In-Won Kim[6,7], and Mathew Williams[2,3]

[1]Division of Environmental Science and Engineering, Pohang University of Science and Technology (POSTECH), Pohang, South Korea, [2]School of GeoSciences, University of Edinburgh, Edinburgh, UK, [3]National Centre for Earth Observation, University of Edinburgh, Edinburgh, UK, [4]Department of Evolutionary Biology and Environmental Studies, University of Zurich, Zurich, Switzerland, [5]Department of Oceanography and International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii at Mānoa, Honolulu, HI, USA, [6]Center for Climate Physics, Institute for Basic Science, South Korea, [7]Pusan National University, Busan, South Korea

Abstract The El Niño–Southern Oscillation (ENSO) drives variations in terrestrial carbon fluxes by affecting the terrestrial ecosystem via atmospheric teleconnections and thus plays an important role in interannual variability of the global carbon cycle. However, we lack such knowledge on decadal time scales, that is, how the carbon cycle can be affected by decadal variations of ENSO characteristics. Here we examine how, and by how much, decadal ENSO variability affects decadal variability of the global carbon cycle by analyzing a 1,801-year preindustrial control simulation. We identify two different aspects, together explaining ~36% of the decadal variations in the global carbon cycle. First, climate variations induced by decadal ENSO-like variability regulate terrestrial carbon flux and hence atmospheric CO_2 on decadal time scales. Second, decadal changes in the asymmetrical response of the terrestrial ecosystem, resulting from decadal modulation of ENSO amplitude and asymmetry, rectify the background mean state, thereby generating decadal variability of land carbon fluxes.

Plain Language Summary The El Niño–Southern Oscillation (ENSO) is an important driver of year-to-year variation of the global carbon cycle due to its impacts on the global climate variability. For example, most parts of the tropical land experience drought during El Niño events, and therefore rainforests and savanna regions do not capture well carbon dioxide compared to normal years because a high temperature and a lack of precipitation during El Niño events lead to less photosynthesis over the tropics. This is a well-known feature in year-to-year variation, but not in decadal time scales due to a lack of long-term observations. Here we examine how, and by how much, decadal ENSO variability affects decadal variation in the global carbon cycle by analyzing a 1,801-year Earth System simulation. We found that two different aspects of decadal ENSO variability, associated with decadal changes in the tropical Pacific Ocean and asymmetric characteristics between El Niño and La Niña, drive decadal change in the terrestrial carbon fluxes. As a result, these two aspects together can explain ~36% of the decadal variability in the global carbon cycle.

1. Introduction

The global carbon cycle, involving oceanic and terrestrial ecosystems, interacts with Earth's climate system on interannual to decadal time scales. Changing carbon (C) uptake by oceanic and terrestrial ecosystems affects atmospheric carbon dioxide (CO_2) concentrations and hence alters the climate system. This interaction complicates the long-term climate projections (Cox et al., 2000) because large uncertainties in the climate/carbon cycle feedback still exist. The terrestrial carbon flux is the primary cause of interannual variability of atmospheric CO_2 growth rate (CGR) (Bousquet et al., 2000; Braswell et al., 1997; Keeling et al., 1995; Rödenbeck et al., 2003) and also has significant variation on a range of time scales. Terrestrial carbon fluxes are sensitive to climate variability because changes in temperature and precipitation in land affect the terrestrial ecosystem processes (Potter et al., 2003; Zhu et al., 2017).

It has long been established that the El Niño–Southern Oscillation (ENSO), a predominant mode of climate variability, leads to interannual variability of the global carbon cycle (Bacastow, 1976; Jones et al., 2001; Keeling & Revelle, 1985; Rayner & Law, 1999). ENSO-induced atmospheric teleconnections regulate the terrestrial ecosystem processes (e.g., plant physiology and soil respiration), especially in the tropics, and the interannual variability of atmosphere-to-land carbon fluxes can be largely explained by these responses (Cox et al., 2013; Liu et al., 2017; Wang et al., 2013; Zeng et al., 2005). Generally, global net terrestrial productivity is reduced during El Niño events due to increased surface temperature and decreased precipitation over most of the tropical land areas, whereas the opposite occurs during La Niña events (Heimann & Reichstein, 2008; Kim et al., 2016). This response of the land ecosystem to ENSO events strongly regulates carbon exchanges and thereby affects atmospheric CO_2 concentration on interannual time scales.

Several studies examined the association between decadal variability of land carbon fluxes and long-term climate variability, such as the Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) (Woodward et al., 2008; Ito, 2011; Zhang et al., 2018). But, the specific impacts associated with decadal ENSO variability on terrestrial ecosystem and their mechanisms still have not been fully established. ENSO is primarily an interannual phenomenon, but it also exhibits decadal modulations of its characteristics, such as amplitude, frequency, skewness, and patterns (An & Wang, 2000; Choi et al., 2011; Gu & Philander, 1997; Imada & Kimoto, 2009; Sun & Yu, 2009). In addition, tropical Pacific sea surface temperature (SST) exhibits pronounced decadal variability (Choi et al., 2013; Zhang et al., 1997), especially in the central Pacific (Stuecker, 2018). We might expect from the strong relationship between ENSO and global carbon cycle that the decadal behaviors of ENSO affect the land C flux on decadal time scales. However, potential interdecadal changes in terrestrial carbon flux due to decadal ENSO variability have not yet been fully examined.

For example, one distinctive observed ENSO characteristic is the amplitude asymmetry between El Niño and La Niña (An & Jin, 2004; Burgers & Stephenson, 1999; Kang & Kug, 2002; Su et al., 2010), which varies from decade to decade (An, 2004, 2009; Duan & Mu, 2006). The positive skewness of ENSO sea surface temperature anomalies (SSTA) induces warm SSTA residuals (i.e., the sum of El Niño and La Niña SSTA) in the eastern tropical Pacific, which can lead to slow changes in the Pacific mean state through rectification (An et al., 2005; Choi et al., 2009; Rodgers et al., 2004; Sun & Zhang, 2006; Timmermann, 2003). We hypothesize that these decadal ENSO modulations may have an important role in the long-term global carbon cycle due to global impacts of ENSO.

However, the impacts of ENSO asymmetry on the terrestrial carbon fluxes are still unclear. Previous studies reported that there is a substantial asymmetric response of the global carbon system to ENSO events, showing that carbon release to the atmosphere during El Niño is greater than carbon uptake from the atmosphere during La Niña years (Qian et al., 2008; Gurney et al., 2012; Chiodi & Harrison, 2014). However, little is known about the specific mechanisms via which the terrestrial ecosystems adjust to this tropical climate forcing on decadal time scales. Here, we aim to provide insights into decadal variability of terrestrial carbon fluxes associated with decadal ENSO variability (i.e., decadal tropical Pacific SST variability and decadal modulations of ENSO characteristics) based on a long-term simulation of a fully coupled climate model. We first investigate the decadal variability of net biome production (NBP), that is, the net atmosphere-to-land carbon flux due to net terrestrial productivity, and how the terrestrial carbon system is affected by decadal variations in tropical Pacific SST. We further examine the effects of ENSO asymmetry associated with decadal ENSO amplitude modulation on the long-term global carbon cycle.

2. Data and Methods

In this study, the preindustrial control simulation of the Community Earth System Model version 1 Large Ensemble (CESM1-LE) was analyzed to examine decadal ENSO variability and its relationship with the terrestrial carbon flux without anthropogenic effects (Kay et al., 2015). The big advantage of this simulation for our purpose is that a 1,801-year integration of the fully coupled Earth system, which consists of the atmosphere (CAM5), ocean (POP2), land (CLM4), and sea ice (CICE) components (Hurrell et al., 2013), is available. The CESM1-LE simulation includes land carbon cycle, diagnostic biogeochemistry calculation for ocean ecosystem, and the atmospheric CO_2 cycle (Lawrence et al., 2012; Lindsay et al., 2014; Long et al., 2013; Moore et al., 2013).

El Niño and La Niña events were defined based on the Niño3.4 index, that is, SSTA averaged over 170–120°W and 5°S to 5°N. El Niño and La Niña events were respectively defined as the upper 20% and lower 20% events of the D(0)JF(1) (December-January-February; DJF) Niño3.4. In this paper, year (0) refers to the developing year and year (1) refers to the decaying year of an ENSO event. The numbers of defined El Niño and La Niña events, 360 for each event, are identical. The ENSO residual is defined as the sum of the El Niño and La Niña composites. As a measure of ENSO amplitude modulation, an index was computed from the 21-year moving standard deviation of D(0)JF(1) Niño3.4 (hereafter, Niño3.4std).

In this study, NBP was mainly used to investigate the terrestrial ecosystem response to decadal ENSO variability. A negative sign of NBP indicates carbon release to the atmosphere, and a positive sign indicates carbon uptake from the atmosphere. Considering delayed responses of the carbon cycle to ENSO (Wang et al., 2016; Zeng et al., 2005), yearly tropical (30°S to 30°N) and global NBP indices were calculated as the sum of NBP anomalies for July(0)-to-June(1) over each domain. As we focus on decadal variability, we applied a 21-year running mean to the Niño3.4 and NBP indices (hereafter, decadal Niño3.4 and decadal NBP anomalies).

We evaluated the performance of decadal SST variability and the simulation of responses of climate and land carbon flux to ENSO in CESM1-LE by comparing with the results from observations. The observational SST data set used is the Extended Reconstructed Sea Surface Temperature (ERSST) data set version 5 from the National Oceanic and Atmospheric Administration (NOAA) (Huang et al., 2017). Monthly climate data (temperature, precipitation) are taken from the University of East Anglia's Climate Research Unit (CRU) Time Series (TS) version 4.03 data set (Harris et al., 2014). The long-term in situ records of atmospheric CO_2 concentrations are obtained from the Mauna Loa Observatory (Keeling et al., 2005). The CGR for time t in months is calculated using the equation (Patra et al., 2005; Sarmiento et al., 2010):

$$CGR(t) = \gamma \cdot [pCO_2(t+6) - pCO_2(t-6)]$$

where γ is 2.1276 (PgC ppm^{-1}) and pCO_2 is the atmospheric partial pressure of CO_2 in ppm. To exclude the effects of anthropogenic emissions on observations for 1960 to 2017, linear trends were removed. Though the magnitudes are a bit different, CESM1-LE overall well simulated the temperature, precipitation, and carbon cycle responses to ENSO events and the decadal SST variability associated with decadal Niño 3.4 (supporting information Figures S1–S3).

3. Results

3.1. Terrestrial Carbon Cycle Variability Associated With Decadal ENSO Variability

Considerable variability of atmosphere-to-land carbon fluxes exists on decadal time scales (Figure 1a). The magnitude of decadal variation in global NBP ($\sigma = 0.14$ PgC yr^{-1}) is ~13% of the magnitude of interannual variability ($\sigma = 1.09$ PgC yr^{-1}). Previous studies suggested that interannual variability of terrestrial carbon cycle can be largely explained by the tropical biogeochemical response to climatic variations (Cox et al., 2013; Liu et al., 2017; Zeng et al., 2005). On decadal time scales, tropical and global total NBP are highly correlated ($r = 0.98$, $P < 0.01$) and their magnitude are almost the same, implying that variations in global land carbon flux are mostly controlled by the tropical terrestrial ecosystem on decadal time scales. Therefore, our focus will be on the response of the terrestrial ecosystem in the tropics.

Next, we calculated the correlation between global total NBP and D(0)JF(1) SSTA to determine which climate phenomena might be associated with decadal variation in global NBP (Figure 1b). A statistically significant negative correlation is found in the Niño3.4 region, suggesting that decadal variability of tropical Pacific SST is associated with decadal variability in global NBP. We also calculated the relationship of global NBP with decadal changes of interannual SST variability, which is defined as the 21-year moving standard deviation (std) of SSTA (Figure 1c). Interestingly, statistically significant negative correlations are also evident in the Niño3.4 region. In other words, decadal changes of ENSO variance are negatively correlated with decadal variability of global NBP.

Both decadal Niño3.4 and Niño3.4std show a distinct negative correlation with global NBP anomalies (Figure 2a). One might think that the negative correlation derives from the cross correlation between two factors, but the cross correlation is relatively weak ($r = 0.31$, $P < 0.01$). In addition, the partial correlation coefficients of global NBP with respect to decadal Niño3.4 and Niño3.4std are almost similar with correlation coefficients, verifying their independence (Table S1). In addition, Figure 2a shows that the two factors independently contribute to decadal NBP changes. For example, the global NBP exhibits high positive value

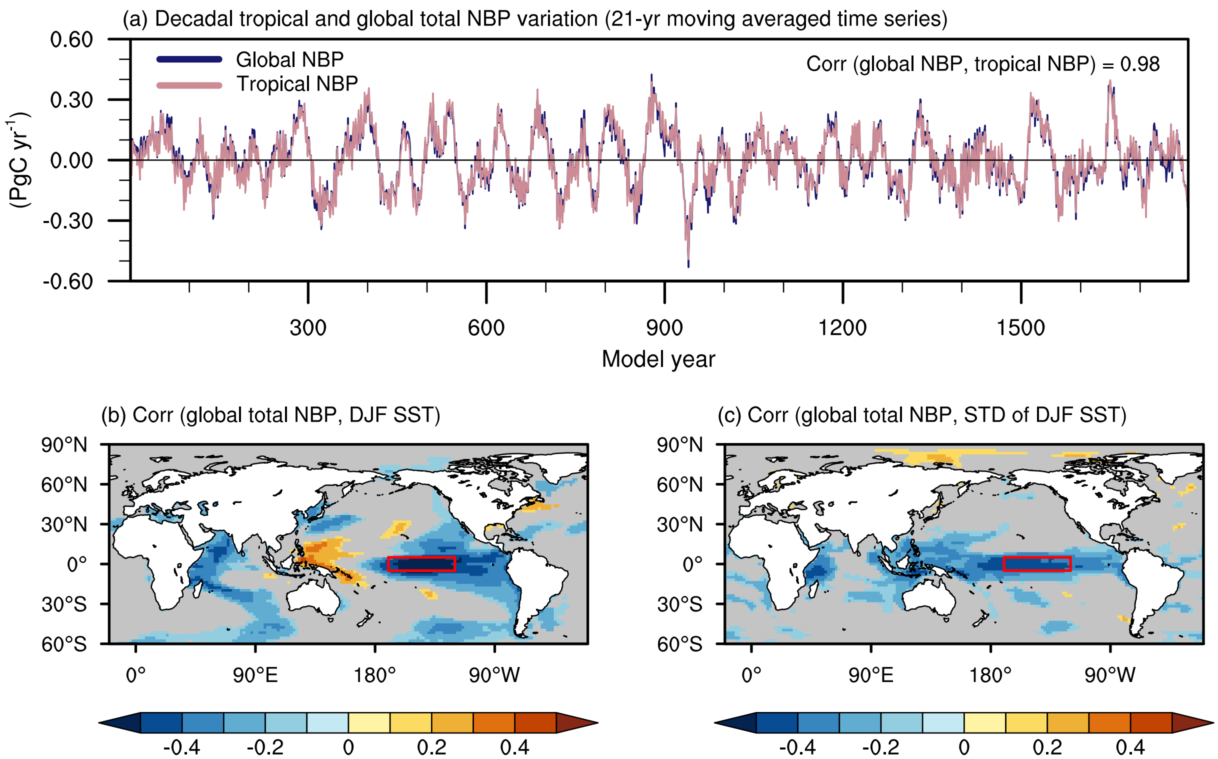

Figure 1. (a) Time series of yearly tropical and global total NBP anomalies for July(0)–June(1). Correlation coefficients of (b) D(0)JF(1) SSTA and (c) 21-year running standard deviation of D(0)JF(1) SSTA with respect to the yearly global NBP. The red box indicates the Niño3.4 region (170–120°W, 5°N to 5°S). Both NBP and SSTA were filtered with a 21-year moving average. Only correlation coefficients that are statistically significant at the 95% confidence level based on a Student's *t* test are shown.

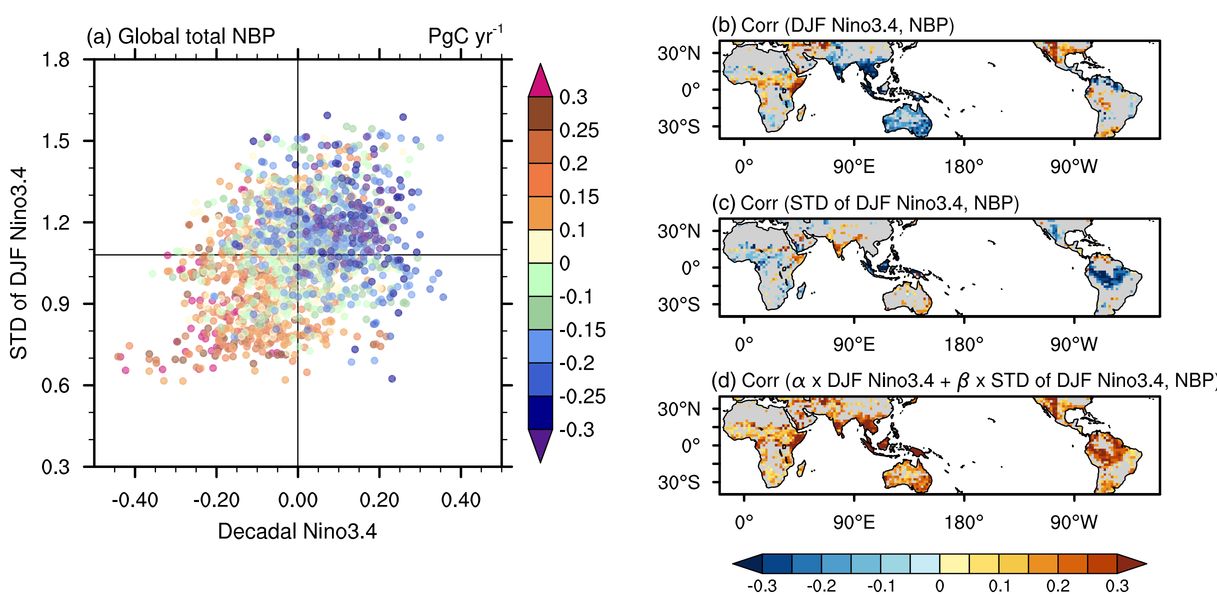

Figure 2. (a) Scatterplot of filtered Niño3.4 against 21-year running standard deviation of Niño3.4 (Niño3.4std). Colors indicate the yearly global NBP anomalies. Partial correlation coefficients of yearly NBP with respect to (b) Niño3.4 and (c) Niño3.4std. (d) Correlation coefficients of the yearly NBP with respect to multiple regressed index of yearly NBP on Niño3.4 and Niño3.4std. Yearly NBP index at each grid point is defined from July(0)–June(1), while Niño3.4 index is for D(0)JF(1). A 21-year moving average was applied to both indices. Only statistically significant values at the 95% confidence level based on a Student's *t* test are shown.

when decadal Niño3.4 is negative and Niño3.4std is weak (lower left quadrant in Figure 2a). In order to further investigate the combined effect of these two factors, we applied multiple linear regression to the global NBP with respect to decadal Niño3.4 and Niño3.4std as predictors. The combined effects of these two factors explained ~36% of the decadal variability of global total NBP ($r = 0.60$, $P < 0.01$). In contrast, the explained variance by decadal Niño3.4 alone is 30% ($r = -0.55$, $P < 0.01$) and by Niño3.4std alone is 18% ($r = -0.42$, $P < 0.01$).

To examine the regions where these factors affect the terrestrial carbon flux, we calculated the partial correlation coefficients of NBP at each grid point with respect to decadal Niño3.4 and Niño3.4std (Figures 2b and 2c). Both factors have significant impacts in equatorial Asia in common, but there are areas in which the two factors affect NBP differently. For instance, decadal Niño3.4 have statistically significant negative correlations with NBP in the northern Amazon, South Asia, and Australia, whereas Niño3.4std is negatively correlated with NBP in the central Amazon. In order to examine the combined impacts of these two factors on NBP in each region, we applied multiple linear regression to the NBP in each grid point with respect to decadal Niño3.4 and Niño3.4std and then calculated the correlation of yearly NBP with this multiple regressed index (Figure 2d). We can see that decadal NBP variation over most of the tropics can be explained largely by these two factors. The mechanisms by which they affect the terrestrial ecosystem are discussed further in the next sections.

3.2. Decadal Change in NBP Induced by Decadal Tropical Pacific SST Variability

ENSO-induced atmospheric teleconnections result in interannual variation over land areas of regional climate which are critical factors for terrestrial ecosystem processes (Ropelewski & Halpert, 1987; Malhi & Wright, 2004; Gu & Adler, 2011). Previous studies have shown that decadal ENSO variability can explain decadal variations of climate in tropical land (Brienen et al., 2012) as well as the existence of decadal variability in ENSO teleconnections (Diaz et al., 2001; McCabe & Dettinger, 1999). On decadal time scales, tropical Pacific SST variations can cause long-term changes in temperature and precipitation in the tropics, which may modulate interdecadal fluctuations of terrestrial carbon flux and thereby affect the global carbon cycle.

To verify this hypothesis, we examine the influences of decadal Niño3.4 on temperature, precipitation, and NBP (Figures S4 and 2b). Except for the southernmost part of North America, tropical land generally has higher air temperature during decadal episodes of a warmer eastern tropical Pacific. In contrast, the precipitation response in the tropics varies greatly by region. While South Asia, equatorial Asia, Australia, and the northern Amazon largely have drier condition, we see precipitation increase in parts of central Africa and many extratropical regions. These decadal climate changes induced by decadal ENSO-like variability greatly affect terrestrial ecosystem. In South Asia, equatorial Asia, Australia, and northern Amazonia, characterized by warm and dry conditions, net terrestrial productivities decrease during anomalously high SSTA decadal episodes in the tropical Pacific, whereas in extratropical regions and the eastern part of central Africa we observe largely an increased NBP resulting from cold and wet conditions.

The responses of climate and C flux over land to tropical Pacific SST variability on decadal time scales are similar to those on interannual time scales (Figure S5). In summary, we found the specific mechanisms by which the decadal ENSO-like variability affects the land C flux. For example, when tropical Pacific SSTA are anomalously warm on decadal time scales, anomalous carbon release to the atmosphere occurs in most of the tropics under either warm or dry conditions. The decadal SST variations in the Niño3.4 region are able to induce long-term climate fluctuations over tropical land areas, which in turn lead to decadal changes in land carbon fluxes.

3.3. Asymmetric Response of NBP to ENSO Events

To understand how ENSO asymmetry affects land carbon fluxes in the tropics, we did the composite analysis of temperature, precipitation, and NBP for El Niño and La Niña events and then calculated the residual (El Niño + La Niña) (Figures 3 and S6). El Niño SSTA are greater in terms of magnitude than those during La Niña in the eastern and central Pacific, which is consistent with previous observational studies (An & Jin, 2004; Burgers & Stephenson, 1999; Kang & Kug, 2002). The spatial patterns of El Niño and La Niña SSTA are not symmetric: La Niña SSTA are typically further extended to the western Pacific. As a result, the SSTA residual shows positive values in the central and eastern tropical Pacific. The asymmetry between El Niño and La Niña results in asymmetrical climate impacts in the tropics. Specifically, positive air

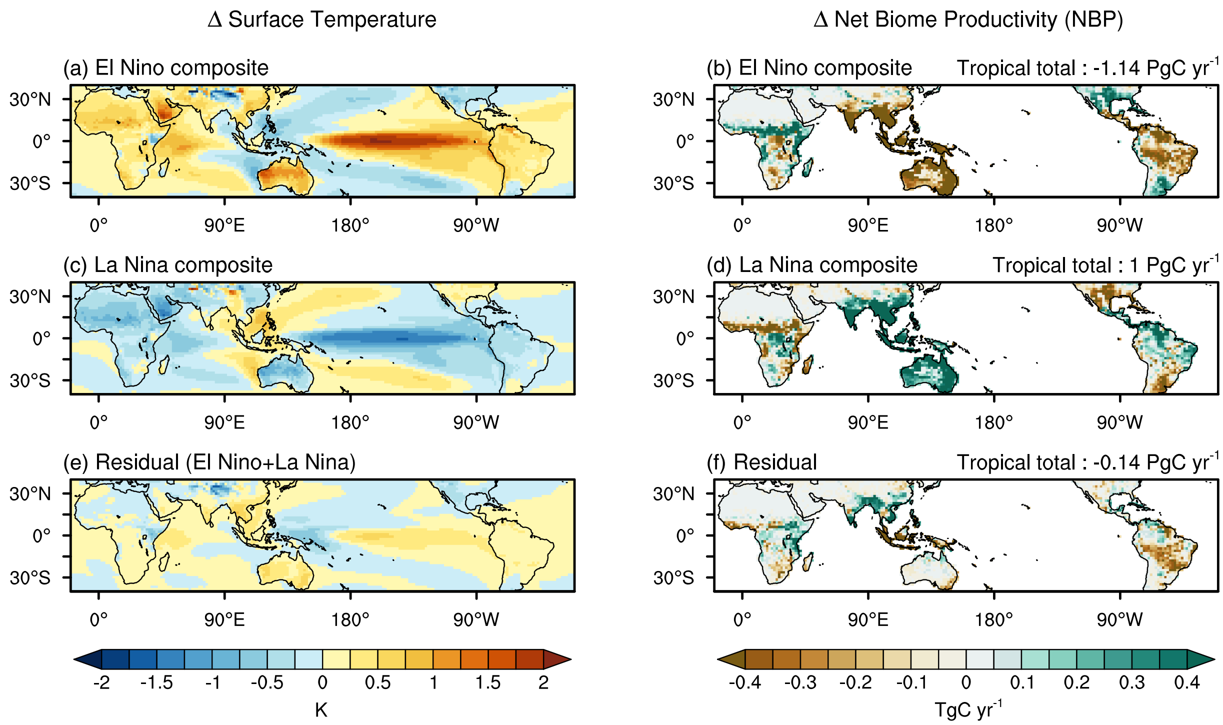

Figure 3. Composite maps of surface temperature anomalies (D(0)JF(1)) (left column) and yearly NBP anomalies (July(0)–June(1)) (right column) for (a, b) El Niño events, (c, d) La Niña events, and (e, f) residual. Only statistically significant values at the 95% confidence level based on a Student's *t* test are shown.

temperature anomalies over land surface during El Niño are typically greater than temperature decrease during La Niña in most parts of the tropics except for Northern Africa. The precipitation residual is relatively heterogenous. In the Amazon, Australia, equatorial Asia, and Africa, precipitation anomalies during El Niño are much greater, but in South Asia the precipitation response during La Niña is much stronger.

These asymmetric climate anomalies and asymmetry of the land ecosystem response itself can both induce asymmetric terrestrial carbon fluxes. During El Niño years, carbon release is dominant with a negative tropical NBP anomaly (-1.14 PgC yr^{-1}) due to anomalously warm and dry conditions. The opposite occurs during La Niña events but with a smaller tropical total NBP anomaly (1 PgC yr^{-1}) compared to that during El Niño. In other words, the carbon release during El Niño tends to be greater than the carbon sink during La Niña. As a result, a negative residual NBP with respect to ENSO events exists (-0.14 PgC yr^{-1}), showing the asymmetric response of the tropical land C fluxes to ENSO events. Especially in equatorial Asia and the Amazon, the negative residual NBP is pronounced. This residual NBP can be accumulated over long periods of time and thereby rectify the mean state of the terrestrial carbon storage.

3.4. Residual Effects of ENSO on Decadal NBP Variability

To investigate changes in residual NBP due to decadal ENSO amplitude modulation, we define strong-ENSO and weak-ENSO periods based on the Niño3.4std. A strong-ENSO period is defined when the Niño3.4std is greater than 1, whereas weak-ENSO period is defined when it is less than 1. Figure 4a shows composites of the global NBP for El Niño years and La Niña years and residual during the whole period, strong-ENSO period, and weak-ENSO period, respectively. Note that the NBP anomalies for the El Niño and La Niña events are calculated by removing each period mean, rather than the mean for the whole time period, so that the anomalies for ENSO composites are not affected by the decadal anomalies.

In general, NBP anomalies for El Niño and La Niña composites are greater during a strong-ENSO period than those during a weak-ENSO period. The residual of global NBP is always negative, reflecting greater land C fluxes during El Niño than during La Niña events. In addition, it is evident that residual NBP is larger during a strong-ENSO period. This is because the asymmetries of temperature and precipitation anomalies are larger when the ENSO amplitude and asymmetry are greater (Figures S7 and S8), which leads to an

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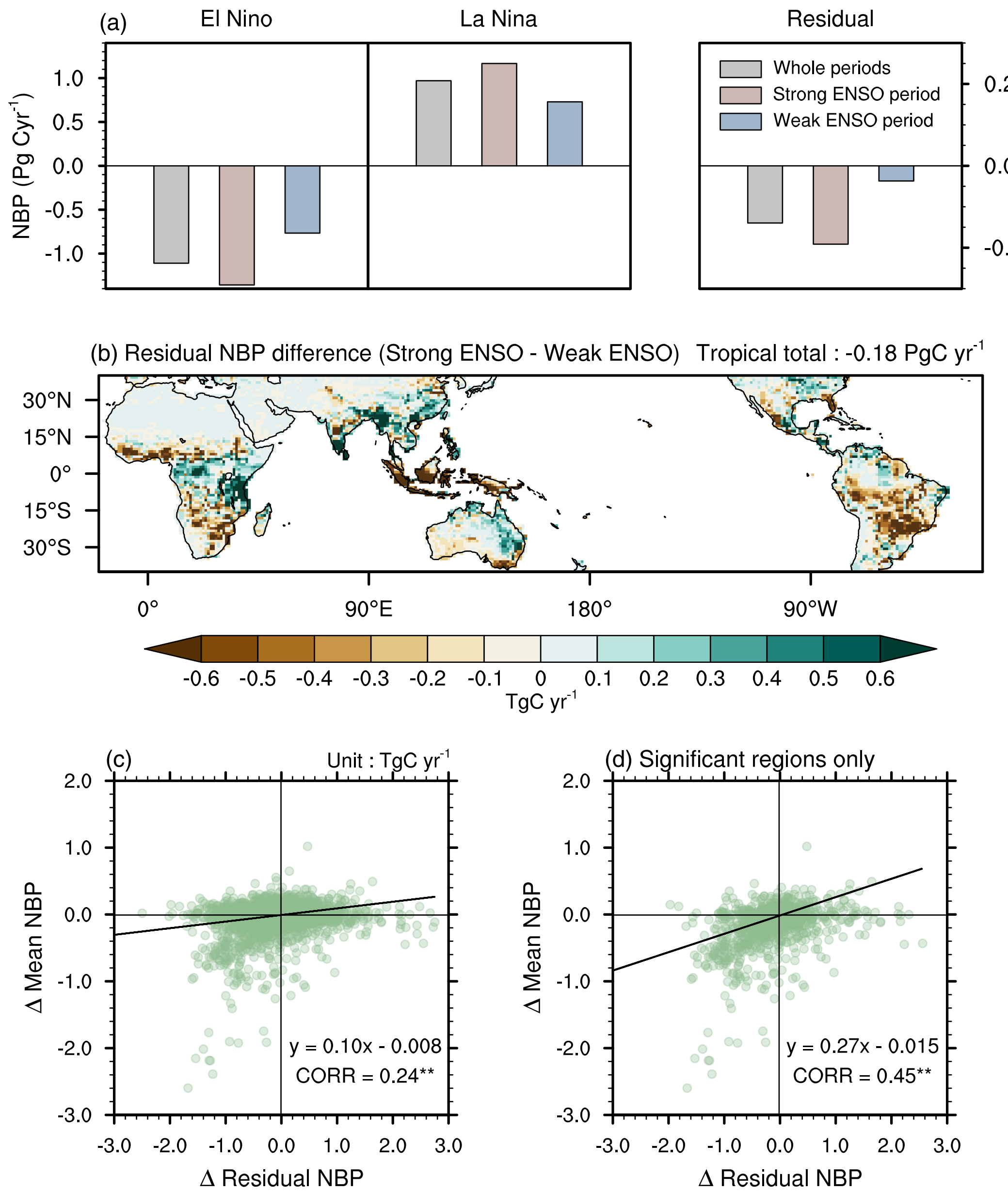

Figure 4. (a) Composite of yearly global total NBP anomaly for El Niño events, La Niña events, and the residual during the whole time period, strong-ENSO period (Niño3.4std > 1std), and weak-ENSO period (Niño3.4std < 1std). (b) Difference of yearly residual NBP between strong- and weak-ENSO periods in the tropics. (c, d) Scatterplots of the residual NBP difference against 21-year moving averaged mean NBP difference (strong-ENSO period − weak-ENSO period). Each dot represents the difference between strong- and weak-ENSO periods at each land grid cell (c) over the globe and (d) in statistically significant regions only (that are shown in Figure 2c). Yearly NBP is defined from July(0)–June(1). Statistical significances are indicated by $^{**}P < 0.01$ and $^{*}P < 0.05$.

intensification of the asymmetric NBP response to ENSO events (Figure S9). These results suggest that residual NBP can be changed by decadal ENSO amplitude modulation. The spatial pattern of the residual NBP difference between strong- and weak-ENSO periods (Figure 4b) is very similar to that of the residual NBP (Figure 3f), implying that asymmetric NBP response is intensified with consistent tendency.

As ENSO amplitude substantially changes on interdecadal time scales (Cobb et al., 2003; Li et al., 2011) and the ENSO-induced residual NBP depends on the ENSO variance, this can lead to decadal NBP variability. Figure 4c shows how much of the residual NBP is locally related to the decadal mean state of NBP. It is clear that the two variables are significantly correlated, which suggests that the changes of residual NBP due to

ENSO amplitude modulation can explain the decadal mean state changes of NBP in many regions. For example, a stronger negative residual NBP due to an increase in ENSO amplitude rectifies the mean NBP during a strong-ENSO period and causes a decadal episode of anomalously negative mean state of NBP. If we consider only regions that have a significant relationship ($P < 0.05$) between ENSO variance and local NBP, the linear relationship becomes even more pronounced (Figure 4d). Therefore, our results suggest that the decadal change in residual NBP, resulting from interdecadal changes in ENSO asymmetry and amplitude, is one of mechanisms that lead to decadal variability of NBP through its rectification into the background mean state.

4. Summary and Discussion

Our analysis suggests the existence of two aspects by which decadal ENSO variability induces interdecadal changes in terrestrial carbon fluxes. First, decadal ENSO-like variability causes interdecadal changes in terrestrial carbon fluxes by causing long-term climate fluctuation. For example, decadal warm phases of tropical Pacific SSTA result in increased temperature and decreased precipitation over large parts of tropical land, thereby reducing terrestrial carbon uptake from the atmosphere. Second, residual NBP effects resulting from decadal changes in ENSO amplitude and asymmetry affect the background mean state of C uptake by the terrestrial ecosystem.

This study shows clear asymmetric land C fluxes associated with ENSO, which can result from two factors. First, since both ENSO and its teleconnections are asymmetric, such asymmetric climate forcing can induce an asymmetric terrestrial ecosystem response. However, even for a symmetric ENSO forcing (i.e., zero skewness), the terrestrial ecosystem response can be asymmetric. This can additionally contribute to the asymmetric NBP anomalies associated with ENSO. For example, the NBP response under anomalously dry condition might be greater than under anomalously wet condition in certain tropical land areas. Therefore, more detailed quantification will be needed for understanding the asymmetric NBP response to ENSO and its decadal changes. NBP is the net signal resulting from different biogeochemical processes, such as net primary production (NPP), heterotrophic respiration (R_h), and disturbances such as fire. Their relative contribution to interannual and long-term carbon cycle variability might differ (Zeng et al., 2005). Accordingly, additional efforts are needed to quantify which components contribute most to decadal NBP variability and rectified mean state changes.

Since the start of the 21st century, the CGR has slowed despite increasing anthropogenic emissions. This reduction is attributed to an increase of terrestrial carbon sinks, which might be caused by a slowdown in temperature-driven ecosystem respiration, CO_2 fertilization effects, and a decrease in land use emissions (Ballantyne et al., 2017; Keenan et al., 2016; Piao et al., 2018). The recent decadal decrease of land surface temperature trend co-occurred with a La-Niña-like decadal SST pattern (Kosaka & Xie, 2013). This change is consistent with our conclusion. Furthermore, we emphasize that the impacts of ENSO on the land C flux might change on both interannual time scales and decadal time scales in the future due to greenhouse warming (Kim et al., 2017) and the resulting potential increase in El Niño variability (Cai et al., 2018). These should be considered in future studies on the linkages between ENSO and the global carbon cycle.

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Data Availability Statement

The CESM1-LE simulations are available on the Earth System Grid (http://www.earthsystemgrid.org). Sea surface temperature data set is from ERSST v5 (https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.v5.html). Near-surface air temperature and precipitation are available from Climatic Research Unit CRU TS4.03 (http://www.cru.uea.ac.uk). The monthly atmospheric CO_2 concentration is from the Scripps CO_2 program (https://scrippsco2.ucsd.edu/data/atmospheric_co2/primary_mlo_co2_record.html).

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